INROADS IN THE NON-INVASIVE DIAGNOSTICS OF BALLISTIC IMPACT DAMAGE

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ABSTRACT

The non-invasive/non-destructive x-ray computed tomography (XCT) technique is a widely applicable and powerful inspection modality for evaluation and analysis of shock and/or impact damage in armor materials, including metallic armors and armor ceramics, as well as materials in general. It presently appears that the non-invasive damage diagnostic approach with XCT provides the only sufficiently effective nondestructive modality for high resolution ballistic impact damage interrogation, spatial characterization, quantification, visualization, and 3-D analysis. Several different examples of material evaluation by XCT analyses are given and discussed in this paper, including both qualitative and quantitative ones. However, the full capabilities of the XCT diagnostic approach have not yet been reached and the beneficial utilization of this new volumetric impact damage knowledge has yet to be extensively applied and exploited. Future developments of the XCT approach will be discussed.

1. INTRODUCTION

Current transformational planning for the survivability requirements of both dismounted personnel and tactical or combat vehicles necessitates significantly improved armor architectural designs and materials to achieve lighter weight, higher mobility and improved survivability. It is, of course, essential that the target protective armor system not be penetrated, and consequently, the predominant focus of armor development, qualification, and validation involves penetration testing. Such penetration testing is necessary but not sufficient for the intelligent development of improved notional armor systems. The occurrence of sub-surface impact damage precedes the occurrence of penetration; consequently, the ballistic performance of the armor material on both first and subsequent strikes may well depend upon the types, extent and morphology of such impact-induced damage. The armor materials research and development paradigm thus needs to be augmented from predominantly penetration testing to include significantly increased and aggressive impact damage characterization and analysis.

In order to logically create armor ceramic materials with significantly improved penetration resistance, one first needs to improve their intrinsic damage tolerance and/or damage resistance. A critical step in that improvement process is the diagnosis and understanding of the physical nature of ballistic impact damage. With a significantly improved characterization of the types, morphologies and extent of the impact-induced damage manifestations involved in a particular ballistic test, one could begin to decipher the active material damage mechanisms and their respective contribution to the loss of the localized target structural integrity leading to penetration. To accomplish this, the non-invasive damage diagnostic approach with x-ray computed tomography, XCT, presently appears to provide the only effective nondestructive modality for high resolution ballistic impact damage interrogation, spatial characterization, quantification, visualization, and 3-D analysis. The XCT impact damage diagnostic approach has been successfully demonstrated on armor ceramics (Wells, 2005, 2006; Miller, et al., 2004; Wells, et al., 2002), Ti-6Al-4V metallic armor materials (Wells, et al., 2004) and, most recently, on a ballistic gelatin target (Wells, 2006). It has also been proposed for inclusion into predictive ballistic impact damage modeling (Wells, 2005).

2. APPROACHES OF XCT ANALYSES FOR DAMAGE EVALUATION

2.1 Initial Work

One of the first investigations of the capabilities of XCT inspection and evaluation for assessing ballistic impact damage was on an impacted, but not penetrated, TiC disk sample, which had been sectioned in half prior

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Inroads In The Non-Invasive Diagnostics Of Ballistic Impact Damage**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Research Laboratory Weapons and Materials Research Directorate Materials Division1/Terminal Effects Division2 APG, MD 21005-5069**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002075.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

to the XCT analysis (Wells, et al., 2002). The paper describes the XCT study of the available half of the disk. The half disk and the meso-damage in it are "visualized" in 2-D cross-sectional XCT scans (or slices), virtual 3-D solid images, and 3-D point cloud images. Figure 1 shows a few XCT slices and their location on a through thickness digital (projection) radiograph of the sample. Figure 2 shows 3-D solid images, some virtually sectioned, of the sample. Figure 3 shows a 3-D point cloud distribution of the meso damage delineating its edges, or boundaries. Although these techniques still continue to be utilized in analyses, they have been utilized in new ways along with more quantitative techniques over the last three to four years.

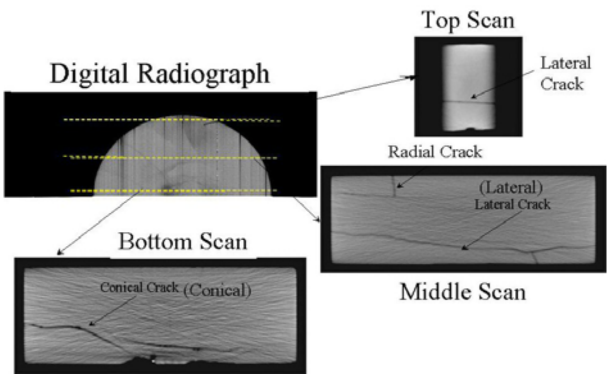


Figure 1. Digital radiograph (DR) and 2-D XCT slices in TiC sample.

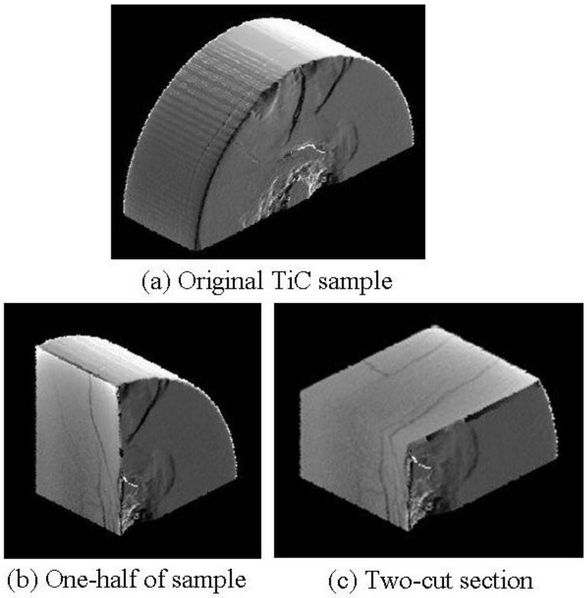


Figure 2. 3-D Solid Visualizations of TiC Sample.

2.2 Subsequent and Current Methods

Several examples of impact damage details previously unobserved and/or uncharacterized before the introduction and utilization of evolving XCT diagnostic damage techniques will be shown and briefly discussed. Included are observations (virtual visualizations) of segmented (virtually isolated) penetrator fragments, novel cracking morphologies including 3-D superimposed hour-glass shaped ring cracks and spiral cracking, 3-D quantification and spatial mapping of damage fraction levels, impact-induced porosity, and 3-D solid visualization for precise analytical positioning. XCT scans (images) are densitometric by nature, thus allowing different materials to be distinguished from one another by their relative attenuation levels for a given set of scanning parameters. Residual penetrator fragments can be digitally isolated from surrounding sample material due to their relatively very high attenuation characteristic. This process of image segmentation, based on thresholding at the appropriate level and binarization, isolates different features of interest depending on the desired analytical focus. Figure 4 is a visualization of residual fragments of a tungsten alloy rod penetrator in a TiB_2 ceramic disk with the TiB_2 material virtually removed. In this case the residual fragments have a columnar distribution. Secondly, the same kind of segmentation with different thresholding and binarization can isolate cracks and entire crack morphologies. Figure 5 shows a virtual surface "fit" relatively tightly to a section of circular, or ring, type cracking in a TiB_2 ceramic disk, again with TiB_2 material removed. This was accomplished by digitally isolating the particular crack type of interest and fitting half of the resultant point cloud. Figure 6 shows a 3-D schematic of the hour-glass nature of these ring cracks. Figure 7 is a point cloud visualization of spiral cracking outside of the penetration cavity in a Ti-6Al-4V sample disk. This type of volumetric damage characterization information, otherwise unattainable, can provide insight into the nature of the evolution of damage and the damage mechanisms.

Since XCT images are digital a wide variety of image processing techniques and approaches can be utilized to improve and analyze them, including some quantitative information like damage fraction if the proper processed images are generated to start with. Figure 8 shows two quantitative plots generated from processed images. They are graphical representations of the axi-symmetric unit damage fraction in a completely penetrated TiB_2 disk as a function of radius (from center of penetration cavity) and depth (distance from impact face). However, one plot includes residual penetrator fragments as part of the nominal material (upper) and in the other they have been digitally (virtually) separated and removed from the TiB_2 material. Thus, the axi-symmetric residual penetrator unit fraction is simply the difference between the two plots. Secondly, Figure 9 shows a histogram plot of impact induced porosity in a XCT slice of the same

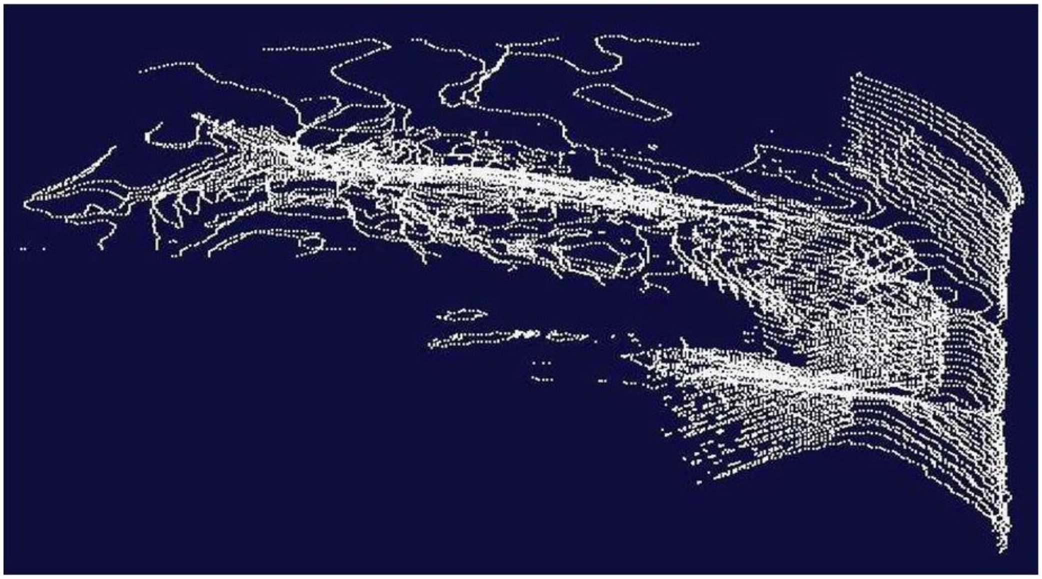


Figure 3. A 3-D point cloud (or wire form) visualization of the entire mesocracking network in the TiC sample.

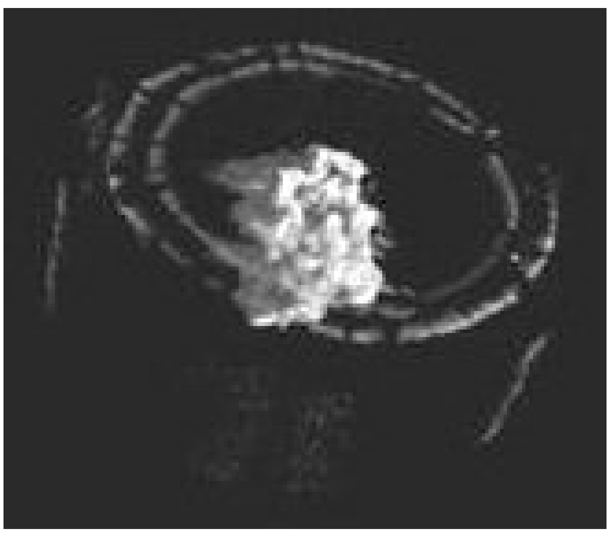


Figure 4. A 3-D visualization of residual penetrator fragments in a TiB_2 sample.

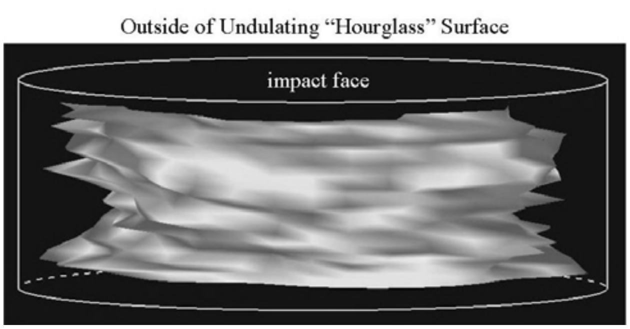


Figure 5. Individual surface fit to section of circular, or ring, type cracking in a TiB_2 sample.

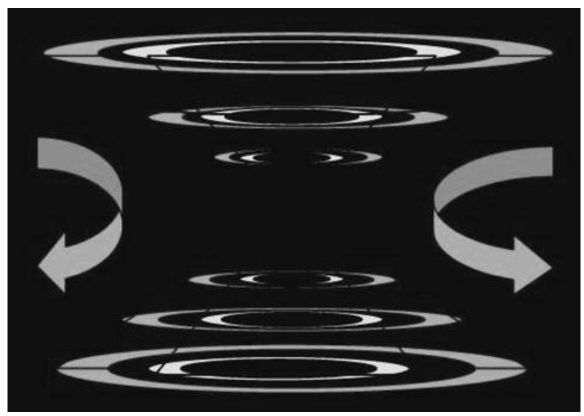


Figure 6. Schematic of ring type cracking in a TiB_2 sample (see Fig. 5).

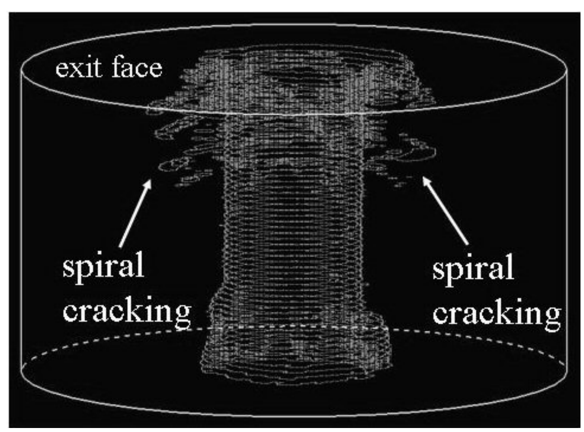
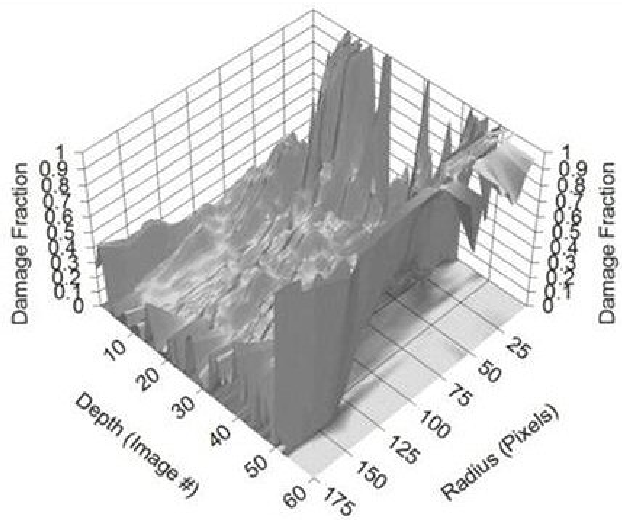
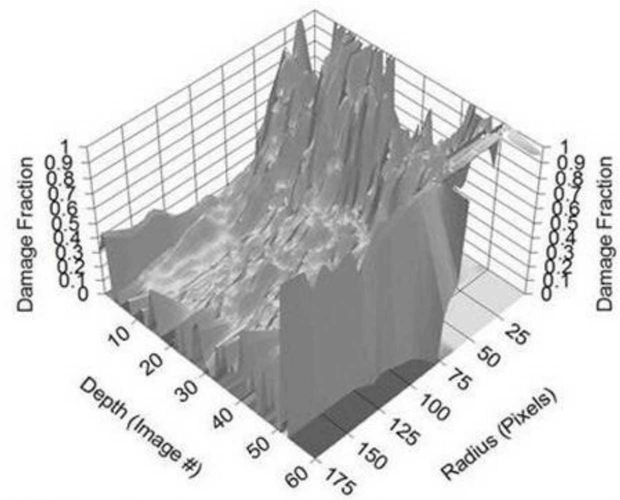


Figure 7. A 3-D point cloud visualization of the penetration cavity and spiral cracking in a Ti-6Al-4V sample.



(a) Residual penetrator present



(b) Residual penetrator virtually removed

Figure 8. Quantitative 3-D unit damage fraction plots in a TiB_2 sample.

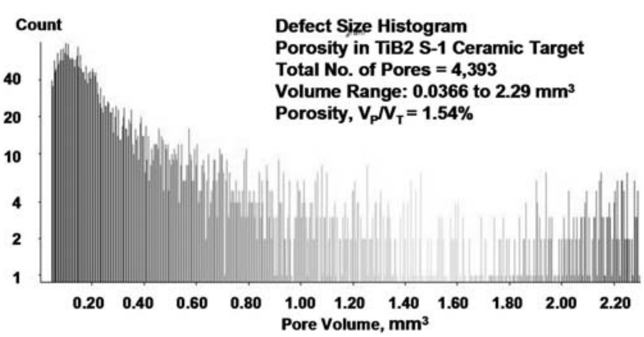
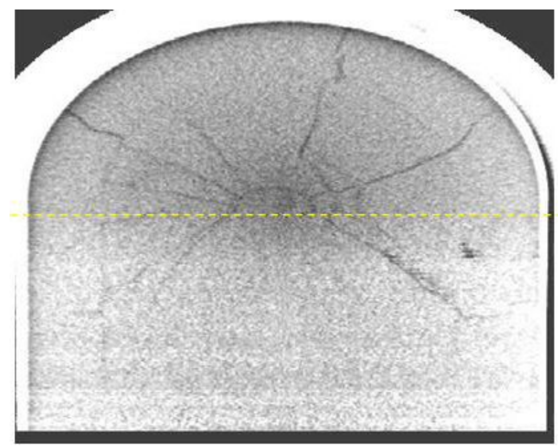


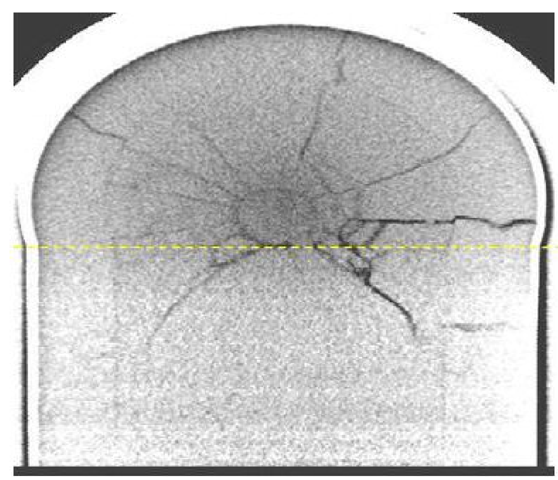
Figure 9. Histogram plot of impact induced porosity in a TiB_2 sample.

TiB_2 disk, which does not include the penetration cavity. Many different types of quantitative data can be determined about various features of ballistic impact damage starting with an appropriate set of processed images (scans).

The utilization of virtual 3-D object sectioning can be easily combined with precise positioning to reveal information about changes in crack and/or other damage type morphologies anywhere in a sample (or scanned volume). Figure 10 shows two virtual 3-D solid visualizations of an impact damaged (ball) ceramic SiC-N disk sample. In both images the top surface is about 2.5-mm below the impact face of the sample. The sample has been virtually half-sectioned perpendicular to its faces in the first image, while the second image has been sectioned about 4.0-mm laterally from the first. This type of analysis can clearly isolate and delineate the physical changes in space of particular damage features.



(a) Half-sectioned visualization



(b) Visualization 4.0-mm from (a)

Figure 10. 3-D visualizations of impact damaged (low velocity) SiC target with precise lateral spacing.

3. DAMAGE EVALUATION AND BALLISTIC DAMAGE MODELING

Damage evaluation and characterization by XCT has not frequently or significantly been applied to validating, modifying, or improving ballistic impact damage models to date. XCT evaluation has been used on occasion to study recovered ballistic impact specimens, but not routinely compared in a well defined quantitative way to impact damage models for such specimens. However, there has been some work combining ballistic impact modeling with post XCT damage evaluation and characterization in AD995 alumina (Bourne, et al., 2006). In this work shock induced damage was generated in a series of AD995 alumina disks at different impact stresses (4, 6, and 7.8 GPa). The experiment used a refined shock-recovery technique to produce one-dimensional loading in the AD995 ceramic samples. After the 6 GPa impacted sample had already been sectioned in half it was scanned and evaluated by XCT. Secondly, many virtual 3-D solid images were created from the scan (slice) data. The modeling as well as the visual and XCT evaluations on the recovered 6 GPa sample indicated that the central part of the sample was well protected from lateral release and was loaded in 1-D. The tomographic 3-D visualizations emphasize the degree of damage that resulted from the impact. Planar damage features, perpendicular to the shock front and readily apparent in the 3-D solid visualizations as shown in Figure 11, result from the reflected tensile pulses due to imperfectly fitted spall and cover plates. Tomographic 3-D visualizations (volume reconstructions) might potentially be used to quantify damage within a target as a function of impact stress (Bourne, et al., 2006).

Furthermore, the unit damage fraction in the 6 GPa sample was plotted as a function of depth (distance from the impact side of the sample – face not directly impacted) for different segmentation threshold values. Figure 12 shows the effects of varying this threshold value for a given XCT slice in the sample. At the top of Figure 12 is the normal distributed gray level slice that the thresholding and binarization were performed on. Below it are four binary damage images for different threshold values in which white indicates nominal ceramic material and black indicates damaged ceramic material within the sample. Changing the threshold changes the relative levels of nominal and damaged material. Figure 13 shows the unit damage fraction plots for each threshold value together on the same graph. The damage fraction plots for the four lower threshold values, including 2350, are grouped relatively close together. However, the damage fraction plot for the highest threshold, 2500, is vertically separated from the others by a larger gap. This type of behavior can be indicative that the particular threshold is too high. Figure 12 shows that a certain physical amount of what is probably nominal undamaged material has been segmented to damaged material at the 2500 threshold. These observations indicate that the threshold of 2500 is not the “best” one to generate a representative plot of damage fraction through the thickness of the AD995 sample. More interesting though is the nature of the changes in damage fraction through the thickness of the sample for a given threshold, since every plot trends in the same way, as expected. The maxima in the plots away from the impact and rear sides of the sample (> 1.5-mm) correspond to the presence of significant planar damage due to reflected tensile pulses, as discussed previously. This type of an approach, including axi-symmetric (vs. radius) – depth type analyses previously discussed, is a logical and reasonable method to obtain a quantitative level of data on shock and impact damage. The issue becomes how to compare quantitative data in this form to ballistic damage model predictions.

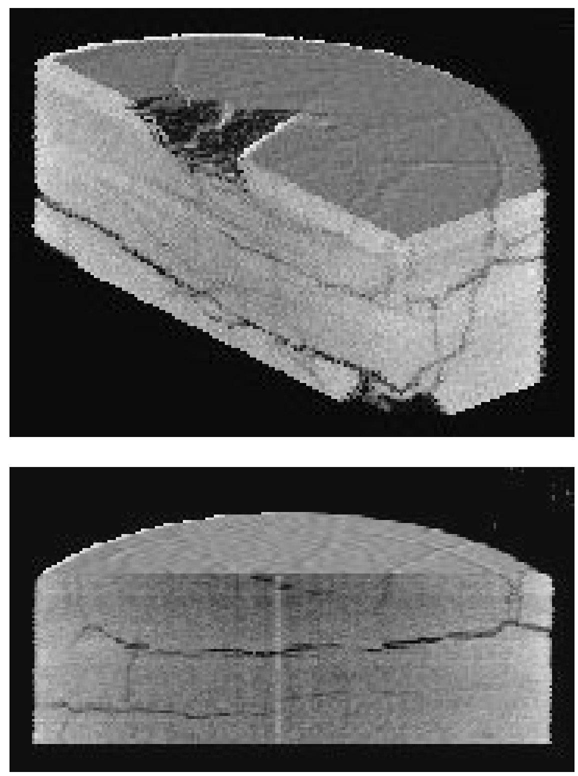


Figure 11. 3-D visualizations of a shock damaged AD995 alumina sample showing extensive planar damage features.

4. SUMMARY AND CONCLUSIONS

The non-invasive/non-destructive XCT technique is a widely applicable and powerful inspection modality for evaluation and analysis of shock and/or impact damage in armor materials, including metallic armors and armor ceramics. Several different examples of damage and other material type (e.g., residual

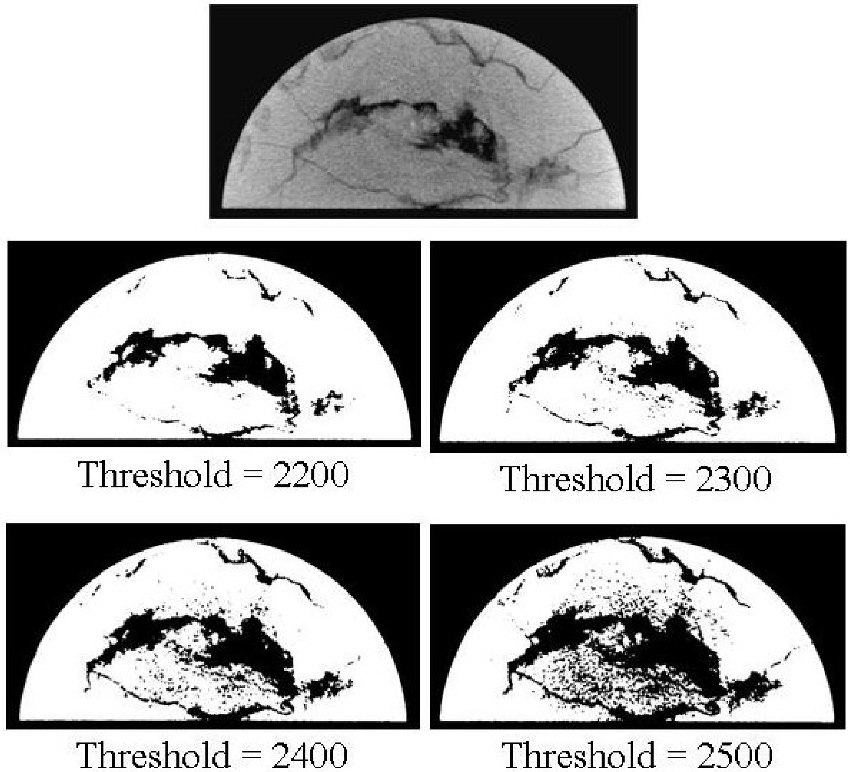


Figure 12. Normal distributed gray level XCT slice in a shock damaged AD995 alumina sample and segmented binary images using different gray level threshold values of same.

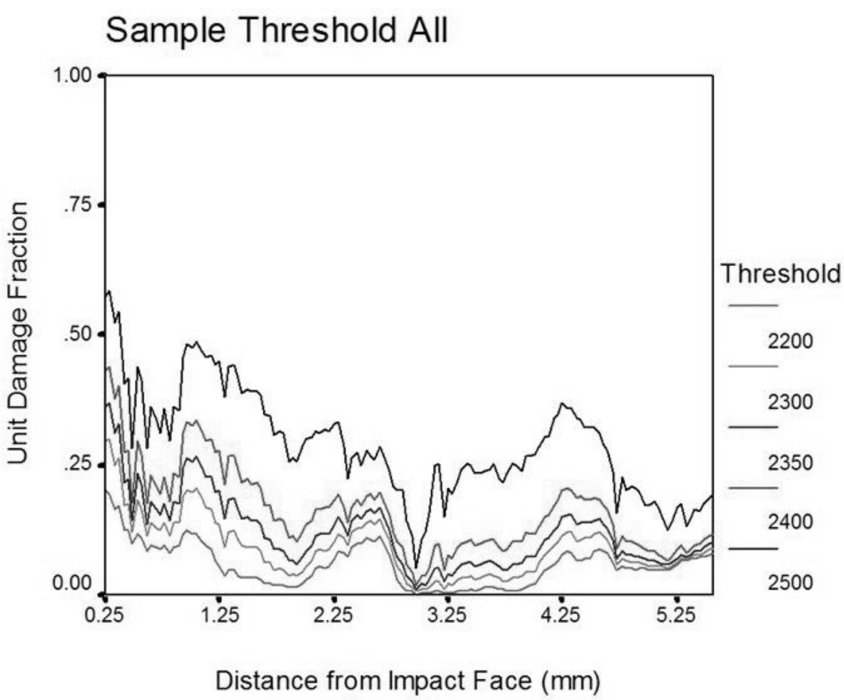


Figure 13. Unit damage fraction plots as a function of distance from the impact side of a shock damaged AD995 alumina sample (See Fig. 12).

penetrator fragments) evaluation by XCT analyses were given and discussed, including observations (virtual visualizations) of segmented (virtually isolated) penetrator fragments, novel cracking morphologies including 3-D superimposed hour-glass shaped ring cracks and spiral cracking, 3-D quantification and spatial mapping of damage fraction levels, impact-induced porosity, and 3-D solid visualization for precise analytical positioning. They span a wide breadth of types of data that can be visualized in various ways. Some preliminary work combining ballistic impact modeling with post XCT damage evaluation and characterization in an AD995 alumina sample was also shown and discussed. Indeed, it presently appears that the non-invasive damage diagnostic approach with XCT provides the only sufficiently effective nondestructive modality for high resolution ballistic impact damage interrogation, spatial characterization, quantification, visualization, and 3-D analysis. Qualitative comparisons using individual XCT scans (images), virtual 3-D solid visualizations, segmented binary images (2-D and 3-D), and point cloud data based on binary images can provide significant and extensive volumetric information. However, the next step is to utilize the types of tools and approaches discussed in this paper, as well as new methods developed in the future, to obtain and provide usable quantitative data for working with ballistic damage models. The full capabilities of the XCT diagnostic approach have not yet been reached and the beneficial utilization of this new volumetric impact damage knowledge has yet to be extensively applied and exploited.

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